Temporal variation in sap-flow-scaled transpiration and cooling effect of a subtropical *Schima superba* plantation in the urban area of Guangzhou

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Abstract

Thermal dissipation probes were used to measure xylem sap flux density for a *Schima superba* plantation growing in the urban area of Guangzhou city, South China. Stand transpiration was calculated by multiplying mean sap flux density by total sapwood area. The peak of sap flux density occurred later in wet season than in dry season. The maximum of daily sap flux density was the highest of 59 g m^{-2} s^{-1} in July and August, and the lowest of 28 g m^{-2} s^{-1} in December. During November 2007- October 2008 and during November 2008-October 2009, the stand transpiration was 263.2 and 291.6 mm, respectively. In the study periods, stand transpiration in wet season (from April to September) could account for about 58.5% and 53.8% of the annual transpiration, respectively. Heat energy absorbed by tree transpiration averaged 1.4×10^8 and 1.6×10^8 kJ per month in the *Schima superba* plantation with the area of 2885 m^2, and temperature could be reduced by 4.3 and 4.7 ^oC s^{-1} for 10 m^3 air.

Keywords: *Schima superba* plantation, sap flux density, stand transpiration, cooling effect

1 Introduction

Transpiration in trees is required for a number of physiological processes and is one of the important processes involved in nutrient transport from soil (Barber, 1995). Forests cover large area and have an important contribution to total energy and mass flows. The studies on forest ecosystem functioning of flows constitute key data sets that are usually used for parameterization of models, especially considering variation over several years. A few techniques have been studied and developed to measure water flow of trees, among which the sap flow method is adopted to

estimate transpiration at the tree level (Granier and Bréda 1996). Sap flux density measured at a given point of tree can be used to estimate whole tee and stand transpiration based on a variety of scaling approaches (Köstner et al. 1992; Martin et al. 1997; Oren et al. 1998). Generally whole-tree transpiration and stand-level water flow are estimated by scaling up sap flux density and sapwood area (Du et al. 2011). Considering the use of thermal energy in the atmosphere by transpiration, rooftop and wall greening are applied to alleviate urban heat island (Yamamoto et al. 2004; Suzuki et al. 2005). In the context of the global warming, it is essential to explore the regulatory role of tree transpiration on the surrounding environment. Since tree transpiration has a cooling effect on the environment, therefore, our aim was to estimate the stand transpiration on the monthly and yearly scales and analyze the cooling effect of tree transpiration by estimating the absorbed heat energy and the decreased air temperature.

2 Results

2.1 Climatic conditions

As shown in Fig. 1, the precipitation mainly occurred during Apr.-Sept. which contributed 81% to yearly total precipitation. The monthly climatic diagram (Fig. 2) showed that the soil volumetric water content was relatively higher during Apr.-Sept. than in the other months. Air temperature increased till Aug. and air relative humidity kept in the high level from Apr. to Sept.. Soil water content was higher during Nov. 2007-Oct. 2008 than during Nov. 2008-Oct. 2009. During Nov.2007-Oct.2008, mean air temperature, mean air relative humidity and mean soil volumetric water content were 69.5 ºC, 21.6% and 36.7%, respectively, while during Nov. 2008-Oct. 2009 they were 72.4 ºC, 23.5 % and 27.5%, respectively. In Nov. 2007-Oct. 2008, mean air temperature, mean air relative humidity and mean soil volumetric water content were 78.7 ºC, 26.1% and 33.6% in wet season and 64.9 ºC, 19.3% and 38.7% in dry season. And in Nov. 2008-Oct. 2009, they were 78.6℃, 27.4% and 30.2% in wet season and 66.1℃, 19.7% and 24.9% in dry season.

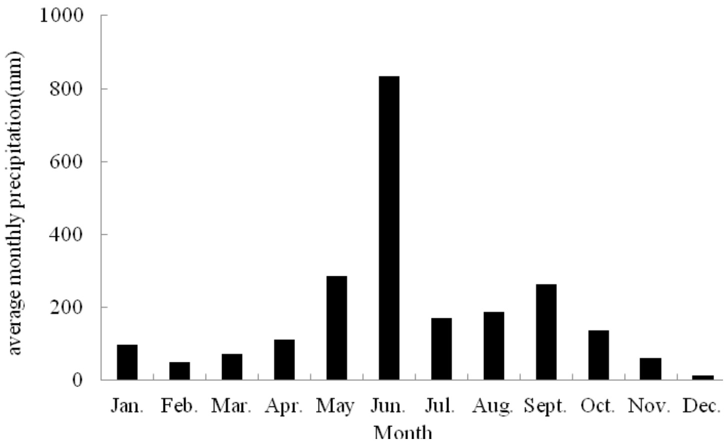


Fig. 1 Monthly mean precipitation in 2008

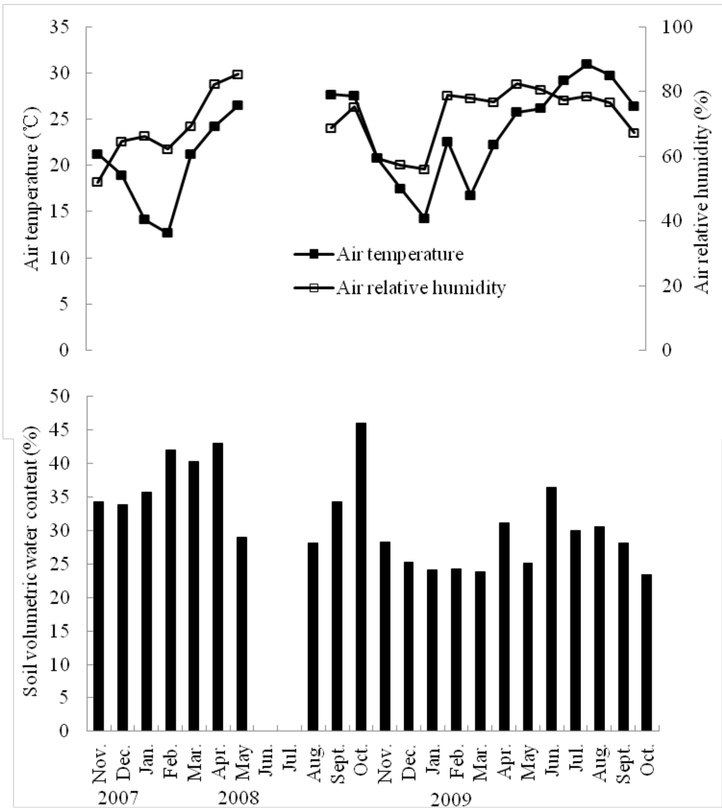


Fig. 2 Monthly variations in air temperature, air relative humidity and soil volumetric water content from Nov. 2007 to Oct. 2009 (The data gap was due to instruments failure)

2.2 Daily change of sap flux density

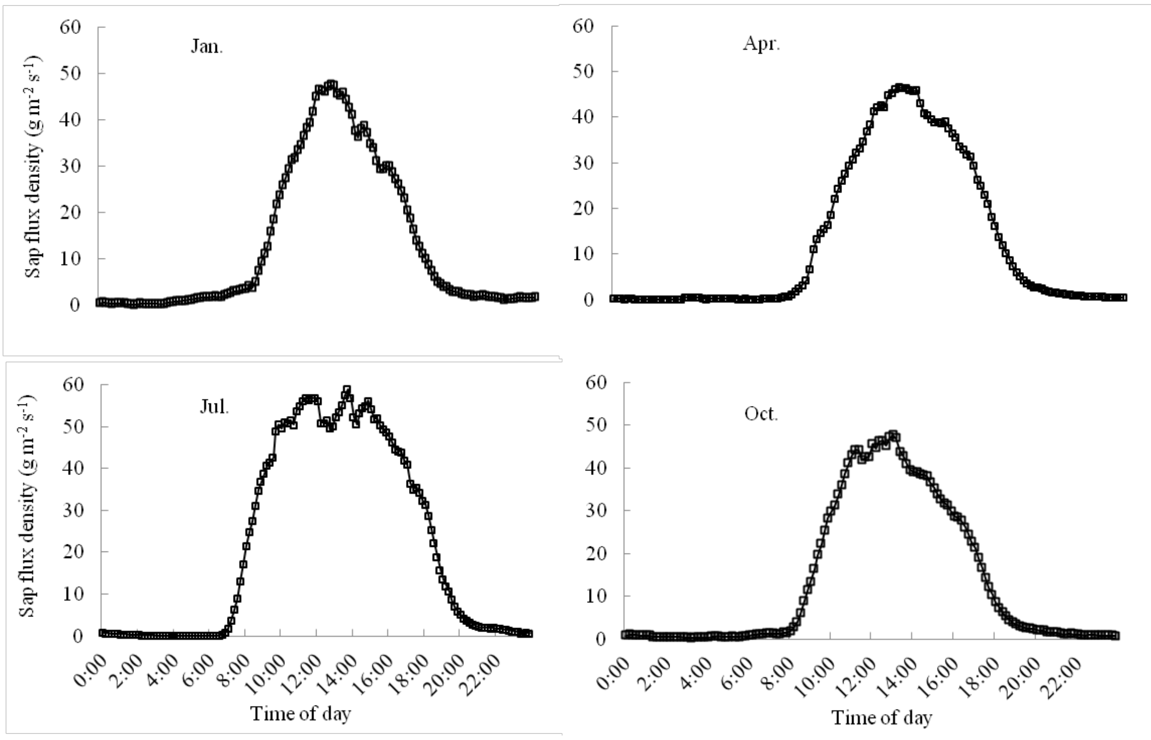


Fig.3 Daily change of sap flux density for four months, Jan., Apr., Jul. and Oct..

(Data were collected in 12 Jan., 8 Apr., 18 Jul. and 29 Oct. Each dot represented the mean for two years)

As shown in Fig. 3, daily courses of sap flux density followed a bell-shaped pattern in all months. Sap flux density reached the maximum of 47.5 and 47.6 g m^{-2} s^{-1} at 12:40 and 13:00 in Jan. and Oct., respectively, while it peaked at 46.5 and 59.0 g m^{-2} s^{-1} at 13:20 and 13:40 in Apr. and Jul.. The maximum occurred earlier in dry season than that in wet season. The maximum of daily sap flux density was the smallest in Dec. (28 g m^{-2} s^{-1}), and was the highest in both Jul. and Aug. (59 g m^{-2} s^{-1}). In June, when precipitation was the highest, sap flux density was not the highest. The sap flow started at about 7:00 in July and at about 8:00 in the other three months.

2.3 Monthly change of sap flow

The maximum of monthly stand transpiration was 34.4 mm occurring in Jul. and the minimum was 14.7 mm appearing in Feb. The monthly stand transpiration during Apr.-Oct. 2008 was higher than that in Nov. 2008- Oct. 2009, but lower than that in the other months. The total stand transpiration was 759.4×10^3 and 841.2×10^3 kg during Nov. 2007- Oct. 2008 and during Nov. 2008- Oct. 2009, which amounted to 263.2 and 291.6 mm, respectively. The averaged monthly

stand transpiration was 20.2 (±4.3) and 26.0 (±5.9) mm in dry and wet season, respectively. Stand transpiration in wet season could account for 58.5% and 53.8% of the yearly transpiration, respectively, in these two periods.

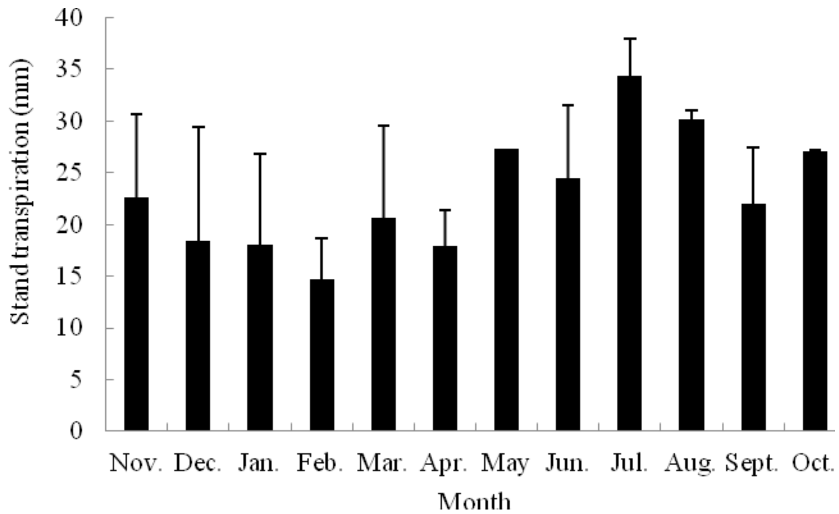
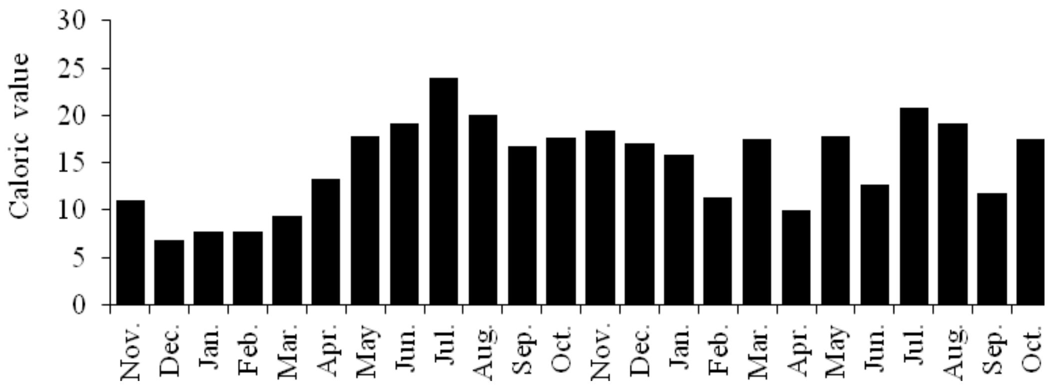


Fig. 4 Monthly mean change of stand transpiration during 2007- 2009

(Bars show standard errors of means. The lack of standard errors in May is due to the missing data in 2008)

2.4 Cooling effect of transpiration

Two equations (eq. (4) and eq. (5)) were used to estimate the heat energy and the decreased temperature by tree transpiration. Fig. 5 shows the thermal value taken away by stand transpiration of studied *S. superba* plantation and the temperature reduction by transpiration for each 10 cubic meter air. The cooling effect reached its maximum during summer season. During the two studied periods, the heat energy absorbed by the *S. superba* plantation averaged 1.4×10^8 and 1.6×10^8 kJ per month. For 10 m^3 air, the temperature could be decreased by 4.3 and 4.7 ºC s^{-1}. The averaged air temperature was lower in July (29.2 ºC) than that in August or September 2009, while the decreased air temperature by tree transpiration was higher in July which was respectively 7.2 and 6.2 ºC s^{-1} per 10 m^3 air in 2007 and 2008. For this experimental area, air temperature was decreased by 0.016 (±0.005) ºC s^{-1} by tree transpiration.



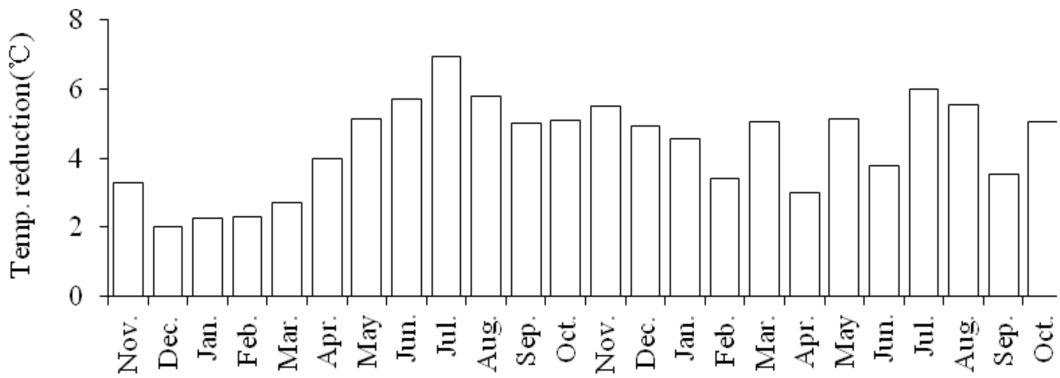


Fig. 5 Cooling effect of stand transpiration of *Schima superba*

(Time period: Nov. 2007 to Oct. 2009)

3 Discussion

Cienciala et al. (2000) estimated the stand transpiration of two *Acacia mangium* plantations and pointed out that the daily tree transpiration averaged 2.3 and 3.9 mm representing the difference of the stand area. Pataki et al. (2000) monitored the sap flux of co-occurring species in a western subalpine forest during seasonal soil drought and found the stand transpiration of 2.6 mm per day despite the different leaf area indices. Wullschleger et al. (2000) estimated the whole-plant transpiration for large maple trees and indicated that whole-tree transpiration was 160 and 45 kg per day for the largest and the smallest trees and canopy transpiration averaged <0.9 mm per day. Wullschleger et al. (2001) estimated the daily transpiration for the multi-species stand averaged 1.1 mm and the total stand transpiration reached 267 mm. Infante et al. (2003) reported that the transpiration of *Quercus ilex* under a Mediterranean condition was 169-205 mm y^{-1}. Huang et al.

(2011) studied *Cyclobalanopsis glauca* transpiration and found the annual stand transpiration reached 836 mm. There were great differences in stand transpiration among the different researches and tree species. In our study, monthly mean stand transpiration was 63×10^3 and 70×10^3 kg for the two studied periods, which was equivalent to 21.8 and 24.3 mm per month, and annual transpiration reached 263.2 and 291.6 mm. The daily stand transpiration was about 0.8 mm. Our result was similar with that of Wullschleger et al. (2001) study. The result from Infante et al. (2003) was lower than that from the other studies because their experiment was conducted during a drought period and a stomatal control avoided the loss of water. Although the soil water content was higher in Nov. 2007- Oct. 2008 than that in Nov. 2008- Oct. 2009, both monthly and annual average stand transpiration were lower, which might indicate the soil water content did not significantly affect stand transpiration of the *Schima superba* plantation. Therefore, even without the water stress, *Schima superba* tree had a lower transpiration.

Pražák et al. (1994) stated that tree growth was viewed as a cooler with water as a coolant. The averaged air temperature reached 27.5 ºC in wet season in this subtropical area. High air temperature could speed up transpiration. In our study, transpiration could absorb the heat energy of 1.5×10^8 kJ per month and decreased the air temperature by 0.016 ºC s^{-1} in the experimental site. The transpiration rate was higher in the wet season which resulted in the strong energy exchange between the plant and the atmosphere. It might cause the more indistinct cooling effect in the wet season with higher air temperature. The interaction of environment with plant is through the flow of energy and all energy is absorbed by a leaf. Some literatures reported the relationship between transpiration and leaf temperature. Rose et al. (1994) studied the whole-plant transpiration in moonlight rose (*Rosa hybrida* L.) and pointed out that the leaf-air temperature difference rapidly decreased from 2.5 ºC to 0.1 ºC after stomates opened. Cook et al. (1964) found that leaves temperature could be decreased by 5 ºC through transpiration. Nakazato and Inagaki (2012) analyzed the plant function as bio-thermal-conditioner using Pothos (*Epipremnum aureum*) and concluded that Pothos showed the air-cooling effect and temperature was dropped down 1 ºC. The studies on the cooling effect of forest transpiration on the surrounding environment are rare even though the ecological service has been recognized. Therefore, in the future, it is necessary to quantify the decreased air temperature by tree transpiration and explore the cooling effect of

transpiration on the urban environment.

4 Conclusion

It is generally accepted to study the tree-level transpiration using the Granier's sensor. Sap flux can be scaled up to the stand level by using sapwood area, which is an advantage for exploring the cooling effect of the forest ecosystem theoretically. But the cooling effect in the *S. superba* plantation was only estimated according to the data from the tree transpiration. In the future, it will be necessary for exploring the ecological effect of the forest ecosystem by monitoring the variation in temperature in the field.

5 Materials and methods

The study site is located in the ecological observation station in South China Botanical Garden, Chinese Academy of Sciences, Guangzhou, China (23°10′N, 113°21′, altitude 41m). Mean annual rainfall is about 1696.5 mm. Mean annual temperature is around 21.9°C. There is a distinct seasonal dynamic with wet season in April-September and dry season in October-March. The experimental site with a northeast exposure is a *Schima superba* plantation planted in the mid-1980s with the area of 2885 m^2. The soil is a loam with pH of 4.0, organic content of 2.3% and total nitrogen content of 0.07%. The annual average leaf area index was 4.3±0.3 based on the monthly-measured data (with LI-2000) from Nov. 2007 to Oct. 2008 and the understory plant is sparse.

5.1 Environmental parameters measurements

Air temperature and air relative humidity were monitored using AT2 and RHT2 sensors (Delta-T Devices, Ltd., Cambridge, UK). Soil volumetric water content at 30 cm soil depth was measured using three sensors (SM200, Delta-T Devices, Ltd., Cambridge, UK) which were inserted into soil layer of 30 cm where the most roots of *S. superba* are distributed.

5.2 Characteristics of sample trees and measurement of sap flux density

There are in total 147 trees in the experimental site (size: 2885 m^2). All the trees were classified into five DBH (the diameter at breast height) classes (6.1-10.0 cm, 10.1-14.0 cm, 14.1-

18.0 cm, 18.1-22.0 cm, >22.1 cm). 15 trees from the experimental site with average DBH 13.5 cm (at 1.3 m above the ground) ranging from 24.2 to 5.8 cm were selected and equipped with sap flow sensors for sap flow measurement. Size characteristics of sample trees are given in Table 1. Sap flux density was measured with Granier type thermal dissipation sensors (Granier 1987). Each sensor consists of two probes with a diameter of 2 mm and a length of 20 mm. the probes were installed on the north side of the trees covered by a plastic protection and an aluminium shield to protect them from rain and direct solar heating. One probe was over the other about 15 cm apart. The upper probe was consistently heated by supplying a constant direct current of 120 mA. The two probes yield a temperature difference that is related to sap flow velocity. Both environmental variables and sap flux density output were read every 30 s, averaged and recorded every 10 min with a data logger (DL2e, Delta-T Devices, Ltd., Cambridge, UK). Data were collected from November 2007 to October 2009. The temperature difference between the two probes was recorded to obtain the sap flux density (J_s, g H_2O m^{-2} s^{-1}), as derived empirically from eq. (1) (Granier 1987):

$$J_s=119\left(\frac{\Delta T_m}{\Delta T}-1\right)^{1.23} \qquad \text{eq. (1)}$$

Where ΔT is the temperature difference between the heated and unheated probes, and ΔT_m is the baseline temperature difference under zero flow conditions.

Sapwood area was estimated according to an allometric relationship (eq. (2)) established based on the other 15 trees near the experimental site.

$$A=0.6841\mathrm{DBH}^{2.0226}\ (n=15,\ R^2=0.994) \qquad \text{eq. (2)}$$

Where A is the sapwood area, DBH is the diameter at breast height.

Total sap flow (g s^{-1}) was calculated by multiplying sapwood area in each class according to eq. (3):

$$E=\sum_{i=1}^{5} J_{si}A_i \qquad \text{eq. (3)}$$

Where J_{si} is the average sap flux density in the DBH class i, A_i is the total sapwood area in the same DBH class. The monthly and annual stand transpiration was obtained by summing sap flux

density over each day and month.

Heat energy (Q, kJ) absorbed by tree transpiration was estimated by multiplying the stand transpiration by the heat of vaporization (eq. (4)).

$$Q=E*\lambda \qquad \text{eq. (4)}$$

Where E is the stand transpiration, λ is the heat of vaporization (kJ kg^{-1}). The air temperature decreased by tree transpiration was calculated according to eq. (5):

$$\triangle T= Q /c/\rho \qquad \text{eq. (5)}$$

Where c is the specific heat capacity (J kg^{-1} ºC), ρ is the air density (kg m^{-3}).

Table 1 Diameter at the breast height (DBH), tree height, canopy size and bark thickness of sample trees for sap flow determination

No.	DBH (m)	Tree height (m)	Canopy size (m×m)	Bark thickness (cm)
1	0.15	10.6	5.6×3.5	0.45
2	0.19	8.5	4.6×3.4	0.60
3	0.13	9.5	3.7×4.1	0.30
4	0.22	11.4	3.5×7.0	0.55
5	0.22	10.1	5.4×5.0	0.70
6	0.10	12.3	4.7×2.2	0.45
7	0.17	8.8	5.1×3.6	0.92
8	0.09	7.8	2.8×2.2	0.52
9	0.09	7.7	3.0×2.4	0.35
10	0.24	12.1	6.3×5.1	0.80
11	0.13	6.6	3.7×3.3	0.37
12	0.06	8.0	2.0×2.6	0.30
13	0.08	12.9	1.4×2.1	0.40
14	0.14	9.5	3.5×2.4	0.42
15	0.07	7.2	2.0×2.0	0.32
mean	0.14	9.5	3.8×3.4	0.49

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